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Research paper

Suitability of salt-marsh foraminifera as proxy indicators of sea level in Tasmania

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ABSTRACT

This paper aims to establish whether contemporary salt-marsh foraminifera from eastern Tasmania are suitably related to elevation and can therefore be used to reconstruct past sea levels. A proxy reconstruction of recent sea-level change in Tasmania is potentially useful because in New Zealand a prominent early 20th century acceleration of sea-level rise has been documented which requires regional confirmation. Forty-three surface samples were collected from two salt marshes in the Little Swanport Estuary. Common species are: *Trochammina inflata*, *Jadammina macrescens*, *Miliammina fusca*, *Trochamminita irregularis* and *Trochamminita salsa*. The latter two species have been previously grouped together as *T. salsa*, but are distinguished here because they occupy distinct vertical niches. We performed regression analyses on the agglutinated foraminifera and their surface elevations using the software package C^2 and tested the accuracy of various regression models by comparing predicted heights of the two transects with surveyed heights. We found that the surveyed heights are closely matched by elevations predicted by Weighted-Average Partial-Least-Squares (WA-PLS) models. These models predict sea level to within ±0.10 m. PLS models showed favourable statistical parameters but were unreliable when used for predictions. Applications of PLS regression models in sea-level reconstructions therefore require caution. We compare our results with other studies from around the world and conclude that microtidal coastlines provide the most advantageous conditions for precise sea-level reconstructions.

1. Introduction

Geological proxies have proven to be invaluable for sea-level reconstructions, providing high-resolution data complementing, and extending beyond, the period of instrumental measurements (e.g., Edwards and Horton, 2000; Donnelly et al., 2004; Gehrels, 2000, 2002; Gehrels et al., 2005, 2006, 2008; Leorri et al., 2008; Kemp et al., 2009). A recent proxy sea-level record from southern New Zealand (Pounawea, Fig. 1) based on salt-marsh sediments shows an acceleration in the rate of sea-level rise in the Southwest Pacific region occurring during the early 20th century (Gehrels et al., 2008). Sea level was fairly stable prior to the 20th century, but between 1900 and 1930 increased to a rate of 2.8 ± 0.5 mm/yr which was maintained throughout the remainder of the 20th century and is in agreement with observations at tide gauges (Gehrels et al., 2008). This New Zealand proxy record takes advantage of the vertical zonation of salt-marsh foraminifera, which relates species distribution to elevation above mean sea level (Scott and Medioli, 1978), and is the first from the southern hemisphere to demonstrate a much faster rise of sea level during the 20th century when compared with preceding centuries.

To substantiate this result, more proxy sea-level records from the Southwest Pacific region are required. In this study we focus our attention on Tasmania. This island is of interest to sea-level scientists as Port Arthur, in southeastern Tasmania, is the location of the oldest tidal bench mark in the world. Here, some of the southern hemisphere's earliest sea-level observations were obtained in 1841–1842 with further observations in the late 1800s, 1972 and 2001 (Pugh et al., 2002; Hunter, 2003). A linear sea-level trend was reconstructed showing a rate of sea-level rise of 0.8 ± 0.2 mm/yr for the period 1841–2003 (Pugh et al., 2002; Hunter, 2003; Hunter et al., 2003). This rate is in contrast with the New Zealand record and also with long Australian tide-gauge records, such as those from Fremantle and Newcastle, which demonstrate rises of 1.4 mm/yr and 2.1 mm/yr during the twentieth century, respectively (Woodworth and Player, 2003). The simple linear nature of the Port Arthur reconstruction potentially obscures any 20th century acceleration of sea-level rise as was found in New Zealand. Tide-gauge records from Tasmania at Spring Bay (since 1991) and Burnie (since 1992) show rates of 3.4 mm/yr and 2.4 mm/yr, respectively (NTC, 2009). Although these records are short, observed rates are much faster than the reconstruction from Port Arthur. A proxy sea-level reconstruction from Tasmania would be useful to extend these instrumental observations

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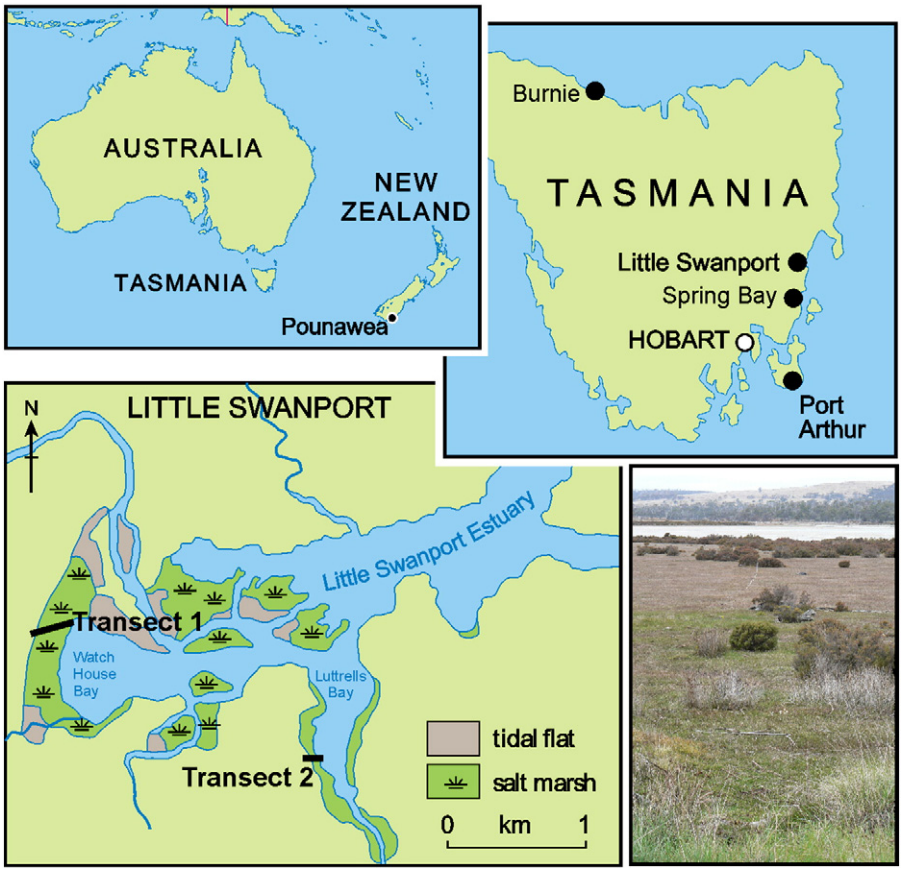

Fig. 1. Location of two sampled transects in the Little Swanport Estuary. Pounawea is the site of a sea-level reconstruction by Gehrels et al. (2008). Historical sea-level observations in Tasmania were made at Port Arthur. Tide gauges are located at Burnie and Spring Bay. The photo shows an overview of the marsh in Watch House Bay. The tall rushes in the foreground are *Juncus kraussii*. The bushy plants in the background are *Tecticornia arbuscula*.

back in time, to test the validity of the Port Arthur sea-level record and to corroborate the early 20th century acceleration of sea-level rise in the region.

The focus of this paper is a quantitative investigation of the distribution of salt-marsh foraminifera in modern salt marshes as a prerequisite for proxy studies of past sea-level change in Tasmania. The majority of research on distributions of intertidal foraminifera has been conducted in the North Atlantic region (e.g., Edwards and Horton, 2000; Edwards et al., 2004; Gehrels, 1994; Gehrels et al., 2001; Horton and Culver, 2008). In comparison, the Australasian region has been covered with studies from New Zealand (Hayward et al., 1999a,b, 2004a,b, 2007, 2010a,b; Southall et al., 2006), eastern Australia (Haslett, 2001: Horton et al., 2003; Woodroffe et al., 2005; Woodroffe, 2009), Japan (Scott et al., 1996), and Indonesia (Horton et al., 2005). Many of these investigations are from mangrove marshes where sea-level reconstructions can be negatively affected by bioturbation and by poor preservation of foraminifera (e.g., Woodroffe, 2009). In this paper we present new foraminiferal data from salt marshes in eastern Tasmania and explore their potential to produce accurate reconstructions of past sea-level changes.

2. Location

An estimated 3300 ha of salt marsh are found in Tasmania, with the majority located along the southeastern and northwestern coasts of the island (Kirkpatrick and Glasby, 1981). Unfortunately, many estuaries have been affected by anthropogenic disturbance and pollution (e.g., Jones et al., 2003). For this study two relatively pristine salt marshes were investigated in the Little Swanport estuary on the east coast of Tasmania approximately 100 km north east of the city of Hobart (Fig. 1), one in the westernmost part of the estuary in Watch House Bay (42°20′31″S 147°55′55″E) and one in the southern part of the estuary in Luttrells Bay (42°20′55″S 147°57′20″E). Settled by Europeans around 1830, the Little Swanport catchment has since been used for agriculture (Rogers, 1991; Tasmania Parks and Wildlife Service, 2007) with moderate anthropogenic impact (e.g. grazing on the Watch House Bay marsh). The estuary has a single outlet into the Tasman Sea, without a depositional bar. The outlet measures c. 150 m during high tide, but is considerably narrower at low tide due to the presence of a low gradient sandy shoreface. A diurnal tidal regime is experienced with a range of 0.7–1 m (Hedge and Kriwoken, 2000) and reducing to 0.6 m in the mid section of the estuary (Edgar et al., 1999). The intertidal zone is dominated by mudflat and salt-marsh habitats (Hedge and Kriwoken, 2000). Little Swanport River, an intermittent watercourse, is the main source of fresh water into the estuary. The salinity of the estuary varies throughout the year and is influenced significantly by rainfall events and discharge variations from the river (Hedge and Kriwoken, 2000). The marsh is underlain by Holocene estuarine sediments that overlie Triassic volcaniclastic sandstones (Forsyth and Gulline, 1979).

The two salt marshes that were investigated exhibit a clear vegetation zonation (Fig. 2). In Watch House Bay the upper marsh is dominated by *Sarcocornia blackiana* and *Juncus kraussi*. The mid to lower sections of the marsh exhibit a cover of *Tecticornia arbuscula* and *Sarcocornia quinqueflora*. The former is denser in the lower part of the marsh. In Luttrells Bay the upper marsh is inhabited by *Poa labillardieri* and *Austrostipa stipoides*. The mid-marsh zone is dominated by *J. kraussi* and *S. blackiana* with some occurrences of *Distichlis distichophylla*. A vegetation mosaic produced by *Samolus repens*, *S. blackiana* and *S. quinqueflora* covers the lower marsh zone, although *S.*

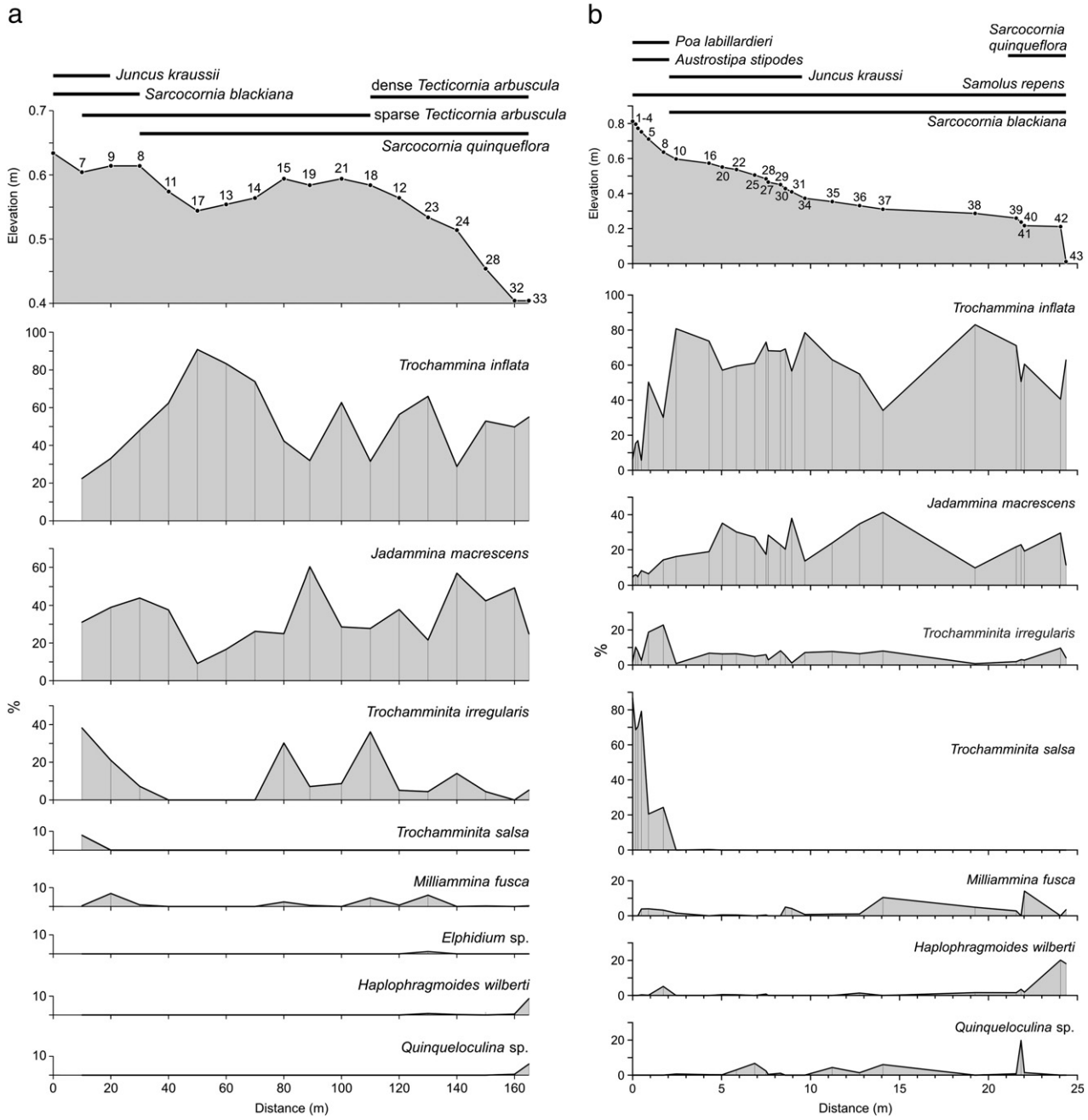

Fig. 2. a. Dominant plants and foraminifera along Transect 1 (Watch House Bay). b. Dominant plants and foraminifera along Transect 2 (Luttrells Bay).

repens dominates the seaward edge. *S. repens* and *S. blackiana* also grow sparsely throughout the upper and mid marsh zones.

3. Methods

Eighteen surface samples, 1 cm in thickness, were collected in November 2006 from a 165 m transect (Transect 1) in Watch House Bay, from the upper marsh to the low marsh (Fig. 1). A further 26 surface samples were collected in April 2007 from Transect 2 in Luttrells Bay. This transect spanned 31.4 m across the marsh with a concentration of samples in the upper marsh and lower sections. The surface samples from both transects were surveyed to a benchmark of a known height enabling each sample to be related to the vertical Australian datum (AD — Geocentric Datum of Australia, 1994).

All the surface samples were stained with rose Bengal for 24 h to distinguish between living and dead foraminifera (Murray, 1991). Although the effectiveness of rose Bengal has been questioned by some authors (e.g., Bernhard et al., 2006), the method is widely used and we applied it in this study so that live foraminifera could be removed from the data analysed (see discussion below). The sampling method and preparation of the samples are described by Gehrels (2002) and Southall et al. (2006). We sampled only the top 1 cm of the salt marsh; any deeper infaunal taxa that may be present were not included. On both our transects we sampled the highest occurrence of foraminifera (0.63 m above AD in Watch House Bay and 0.81 m above AD in Lutrells Bay). Samples were wet sieved between 0.063 and 0.5 mm and were split using a wet-splitter (Scott and Hermelin, 1993) so that a minimum of 300 foraminifera were counted (Appendix A). The lowest count included in the statistical analyses is 124 (sample 38). With the low diversity faunas in this study this count is sufficient (Patterson and Fishbein, 1989). The samples were preserved in methanol and analysed in liquid.

Using the dead surface foraminifera data set, statistical analyses were conducted using the software package C^2 (Juggins, 2003) to assess the relationship of the modern foraminifera and elevation of the marsh. In C^2 various regression models can be used to explore the usefulness of the foraminifera as sea-level indicators. These depend on the types of distribution of the foraminifera along the height gradient. Taxa showing a unimodal relationship with elevation, peaking in abundance at an optimal elevation, require a weighted average statistical model. For taxa that increase or decrease in abundance with elevation a linear statistical model is more appropriate. Detrended Canonical Correspondence Analysis (DCCA) can be used to assess which method should be used with a particular training set (Birks, 1995; Lepš and Šmilauer, 2003; Horton and Edwards, 2006). DCCA calculates the gradient length (for axis 1) measured in standard deviation (SD) units. If the gradient is shorter than 2 SD units then linear regression models are the most appropriate for the dataset. The DCCA of the foraminiferal training set of both transects combined and with elevation being the only environmental variable, produced a primary axis gradient length of 1.7 SD. As this is close to 2, we applied Partial Least Squares (PLS) and Weighted Average Partial Least Squares (WA-PLS) regressions and compared the statistical parameters of both models.

For each model we calculated the coefficient of determination (r^2), root mean squared error (RMSE) and maximum bias of the training set. The root mean squared error of prediction (RMSEP) was calculated by the leave-one-out cross validation method ('jack-kniving'). This gives a representation of the predictive capabilities of the modern training set (Birks, 1995) to infer the elevations at which sediments containing the fossil assemblages were deposited (i.e. former marsh-surface elevations).

In general our taxonomy follows Hayward et al. (1999b), but they considered *Trochamminita salsa* (Cushman and Brönnimann, 1948) and *Trochamminita irregularis* Cushman and Brönnimann, 1948 to be synonymous. We recognised morphological variations and have decided to retain these two species which appeared to have different vertical distributions. *T. irregularis* with a very rough texture and rounded test was found throughout the salt marsh. Often the chambers are collapsed and growing in a uniform manner. The later chambers sometimes become globular and are arranged irregularly. A single, lipped aperture is located on the face of the final chamber. *T. salsa* is located only in the upper marsh. The test texture is less rough and more ovular in shape. Inflated chambers grow in a uniform way without irregularities. The majority of specimens had two lipped openings for apertures on the face of the last chamber (Hayward et al., 1999b).

T. irregularis and *Labrospira salsa* were first described from Trinidad by Cushman and Brönnimann (1948) but the type locality is not well constrained (mangrove swamp, west coast Trinidad). Saunders (1957) emended these two species with new material from 'Trinidad's east and north coasts (not topotypic) and created the new combination *T. salsa*. He made no comments on elevational distribution but noted "The new information shows that *T. salsa* and planispiral forms of *T. irregularis* only differ in chamber shape and coarseness of wall texture". He also noted that "*T. irregularis* Cushman and Brönnimann, emend. Saunders, shows all transitions of test form from wholly planispiral to almost completely irregular." Indeed, we found little difference in grain size between the two species (compare Plate 1, Figs. 11 and 17). A detailed discussion on whether the morphological differences between the two "types" is of real specific significance is beyond the scope of this paper. However, the contrasting distributions of the two "types" is potentially important for sea-level reconstructions, especially because both are found in fossil material (Callard, 2007). Although in New Zealand *T. salsa* appears to be restricted to the upper marsh and morphological types have not been distinguished (Hayward et al., 1999a; Hayward et al., 2004a,b; Southall et al., 2006), we note that in marshes in Oregon (USA) *T. irregularis* is common whereas *T. salsa* is absent (Hawkes et al., 2010).

4. Results and discussion

Overall, a horizontal succession of foraminifera can be seen along both transects with *T. salsa* clearly restricted to the upper marsh environment. Comparison with other sites in Australia is impeded by a lack of studies, but this pattern has also been noted from other sites in New Zealand (Southall et al., 2006) where *T. salsa* is also an important high marsh sea-level indicator (Gehrels et al., 2008). The overall zonation in the Tasmanian marshes, however, is less well defined than in New Zealand. The dominance of *T. inflata* and the low abundances of *M. fusca* and *H. wilberti* suggest that salinities are near 35‰ in the Tasmanian marshes. In lower salinity situations zonation is generally better developed (Hayward et al., 2004b).

4.1. Transect 1 (Watch House Bay)

4.1.1. Dead foraminifera

Transect 1 spans heights between 0.404 m and 0.634 m AD. The distribution of the dead foraminiferal abundances is shown in Fig. 2a. The marsh is dominated by *T. irregularis*, *Jadammina macrescens* and *Trochammina inflata*, with a minor contribution of *Miliammina fusca*. The highest sample contained only two foraminifera and was therefore excluded from the dataset. *T. salsa* makes its only appearance in the top of the marsh (sample 7). *T. inflata* is the dominant species in a small depression in the high marsh (40–70 m). At the lower end of the transect we find minor appearances of *Haplophragmoides wilberti*, *Elphidium* sp. and *Quinqueloculina* sp.

4.1.2. Live foraminifera

The number of living specimens counted in each sample was significantly lower than the dead foraminifera. Live foraminifera in the top eight samples, in particular, were very sparse with three samples void of any living foraminifera (Appendix A). The distribution of live foraminiferal abundances is similar to the dead foraminifera with *T. inflata* being the dominant species throughout the transect. *J. macrescens* and *T. irregularis* also occur in high numbers although were not consistently present.

4.2. Transect 2 (Luttrells Bay)

4.2.1. Dead foraminifera

Twenty-six surface samples were counted from Transect 2 between 0.012 m AD to 0.812 m AD. The vertical range of the foraminifera analysed in Lutrells Bay is therefore larger than in Watch House Bay. The distribution of the dead foraminiferal abundances is shown in Fig. 2b. The four highest samples are dominated by *T. salsa*. This species is much more abundant than in Watch House Bay and was found in seven samples. The remainder of the transect is dominated by *T. inflata* and *J. macrescens*, with minor occurrences of *T. irregularis*, *Quinqueloculina* sp. and *M. fusca*. *H. wilberti* is relatively important at the lower end of the transect.

4.2.2. Live foraminifera

The distribution of the live foraminifera is similar to that of the dead assemblage. Only in five samples did the living count exceed half of the dead count with the majority of samples being significantly lower. However, in comparison to Transect 1, there are more living foraminifera overall (Appendix A). The main difference between the live and dead assemblages is the higher relative abundance of *Quinqueloculina* sp. in the live assemblage.

4.3. Statistical analyses

It has been suggested that total (live and dead) foraminiferal assemblages most accurately represent the modern environment and are, therefore, most suitable for palaeoenvironmental reconstructions

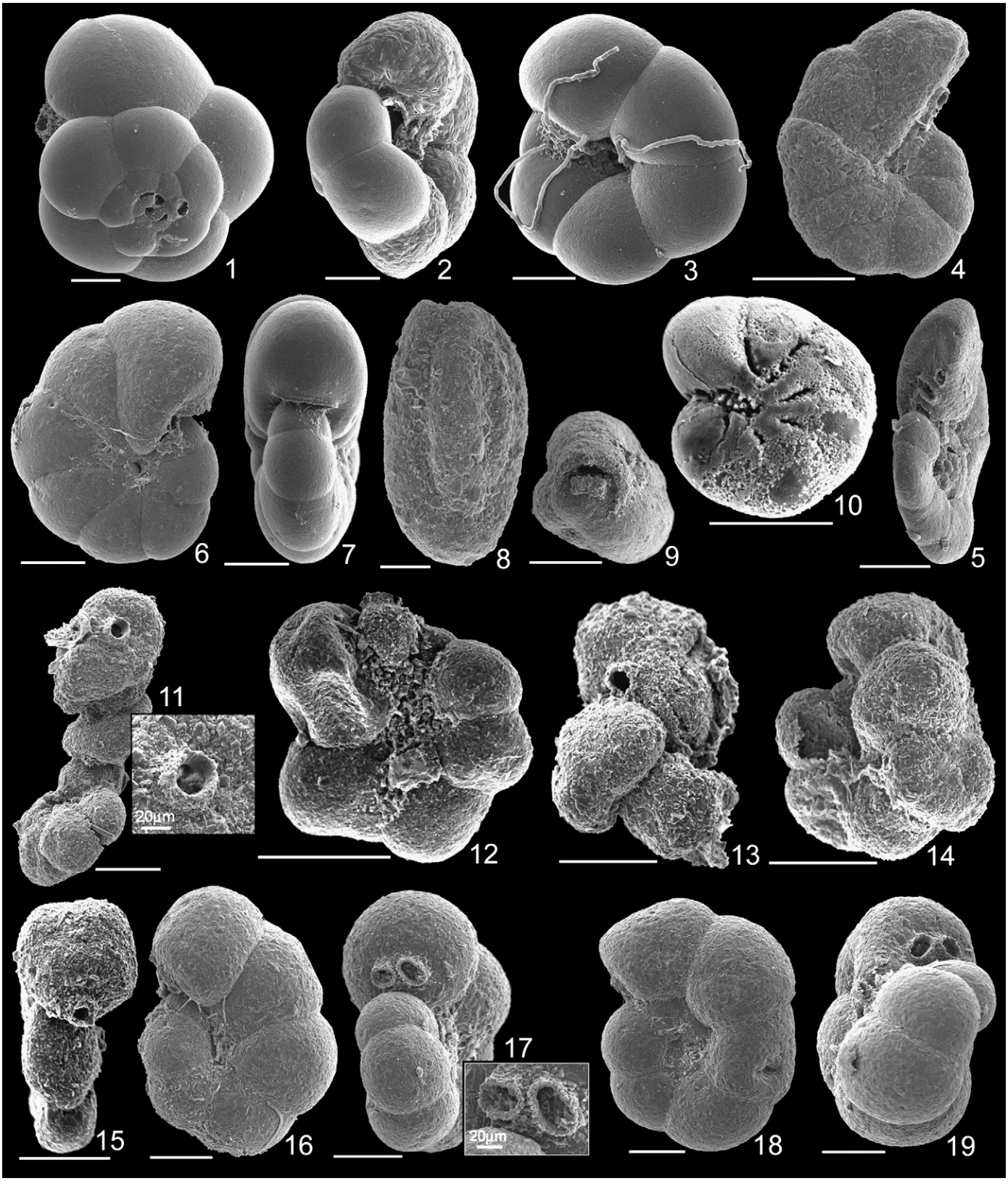

Plate 1. 1–3 *Trochammina inflata* (Montagu 1808); 4–5 *Jadammina macrescens* (Brady 1870); 6–7 *Haplophragmoides wilberti* Anderson 1953; 8–9 *Miliammina fusca* (Brady 1870); 10 *Elphidium* sp.; 11–15 *Trochamminita irregularis* Cushman and Brönnimann 1948, with a close up of the aperture in 11; 16–19 *Trochamminita salsa* (Cushman and Brönnimann 1948) with a close up of apertures in 17. Scale bar 100 μm unless otherwise stated.

(Scott and Medioli, 1980). The living foraminiferal assemblage is, however, composed of species that are in equilibrium with the dominant environmental variables at the time of sampling. This means that the assemblage can change over time in both species type and quantity (Murray, 1991; Horton et al., 1999). This is evident in the Little Swanport estuary where living individuals of *Quinqueloculina* sp. appear to occur in

Table 1
Statistical parameters of the dead foraminifera training sets for both transects ($N=43$), transect 1 (Watch House Bay) only ($N=17$), and transect 2 (Lutrells Bay) only ($N=26$). Three components are calculated for PLS and WA-PLS. RMSE — root mean squared error; r^2 — coefficient of determination, RMSEP — root mean squared error of prediction; r^2 (jack) — coefficient of determination of the jack-knifed cross-validation; Max bias (jack) — maximum bias of the jack-knifed cross-validation; PLS — Partial Least Squares regression; and WA-PLS Weighted Average Partial Least Squares regression.

	RMSE (m)	r^2	RMSEP (m)	r^2 (jack)	Max bias (jack) (m)
Total training set					
PLS (1)	0.13	0.36	0.14	0.30	0.46
PLS (2)	0.09	0.67	0.13	0.42	0.43
PLS (3)	0.08	0.76	0.09	0.68	0.16
WA-PLS (1)	0.12	0.48	0.13	0.42	0.41
WA-PLS (2)	0.09	0.72	0.10	0.65	0.15
WA-PLS (3)	0.08	0.75	0.10	0.66	0.14
Transect 1 training set					
PLS (1)	0.06	0.14	0.07	0.03	0.15
PLS (2)	0.06	0.16	0.07	0.02	0.14
PLS (3)	0.05	0.46	0.07	0.03	0.13
WA-PLS (1)	0.05	0.43	0.06	0.22	0.09
WA-PLS (2)	0.05	0.50	0.06	0.31	0.10
WA-PLS (3)	0.05	0.51	0.39	0.32	0.73
Transect 2 training set					
PLS (1)	0.14	0.50	0.15	0.44	0.41
PLS (2)	0.11	0.69	0.14	0.55	0.40
PLS (3)	0.08	0.85	0.10	0.75	0.20
WA-PLS (1)	0.12	0.63	0.13	0.56	0.37
WA-PLS (2)	0.09	0.82	0.11	0.72	0.16
WA-PLS (3)	0.07	0.87	0.10	0.78	0.13

higher abundance at Luttrells Bay compared to Watch House Bay salt marsh. The timing of sampling (November in Watch House Bay and April in Luttrells Bay), however, may be an influence, which highlights the potential seasonal bias that is introduced when using live assemblages in palaeoenvironmental reconstructions. The dead assemblage represents an accumulation of tests and associated taphonomic changes that are averaged over several years (Murray, 1991, 2000). It is reasonable to assume that the dead assemblage is most similar to the fossil assemblage and most suitable for palaeoenvironmental reconstructions (Murray, 1991, 2000; Goldstein and Watkins, 1999). It was therefore decided to use only the dead assemblage for the statistical analyses. The calcareous foraminifera *Elphidium* sp. and *Quinqueloculina* sp. were excluded from the training set as they were rare in the dead counts compared to the living fraction, indicating poor preservation in the salt-marsh environment.

A PLS regression model was used on 43 samples and six species from the two transects in Little Swanport estuary. The relationship between the observed elevation and predicted elevation is fairly strong ($r^2_{jack}=0.68$ for component 3). The results indicate that this model can reconstruct former sea levels to a precision of ± 0.094 m ($RMSEP_{jack}$). A WA-PLS regression model was also applied to the same training set. Comparisons of the statistical parameters are shown in Table 1. The WA-PLS model (component 3) has a lower r^2_{jack} of 0.66 and a slightly higher $RMSEP_{jack}$ of ± 0.098 m.

When sample elevations inferred from the regression models are compared with surveyed elevations (Fig. 3) it is apparent that both

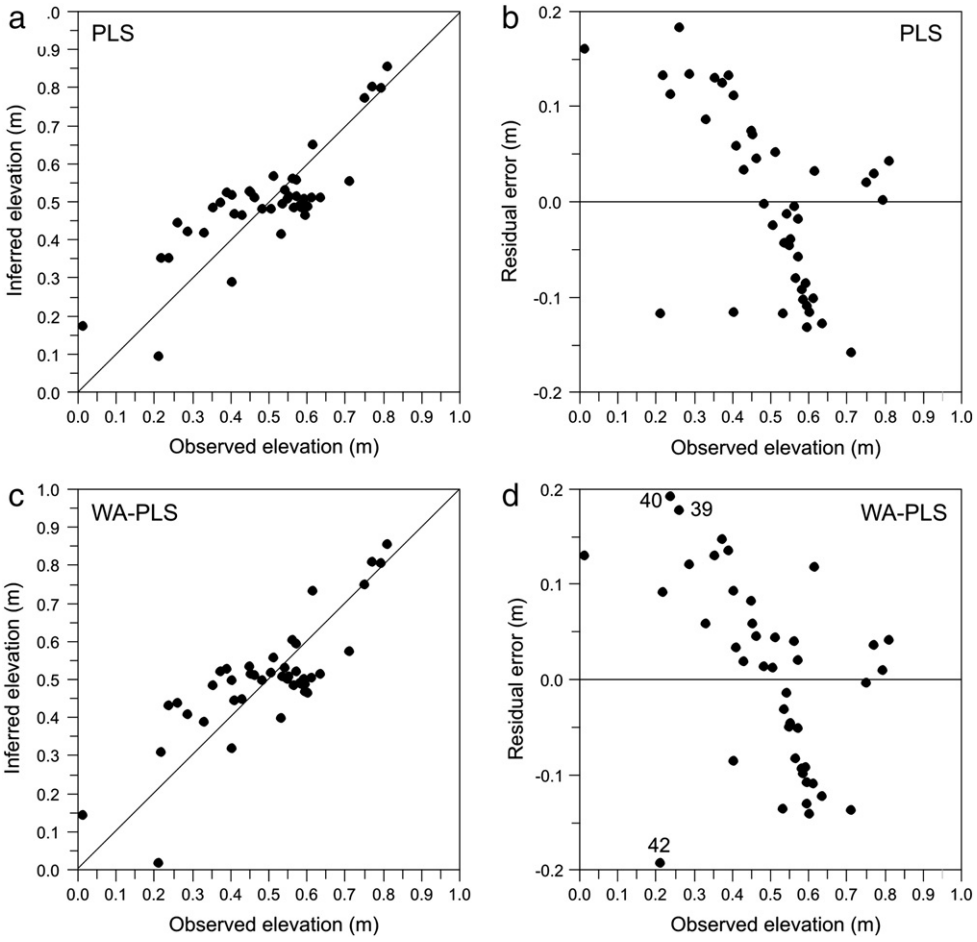

Fig. 3. Sample elevations inferred by the PLS (a) and WA-PLS (c) regression models, compared with observed elevations. Residual errors of PLS (b) and WA-PLS (d) are calculated by subtracting the observed elevations from the inferred elevations. Largest 'outliers' in (d) are samples 39, 40 and 42 (see text).

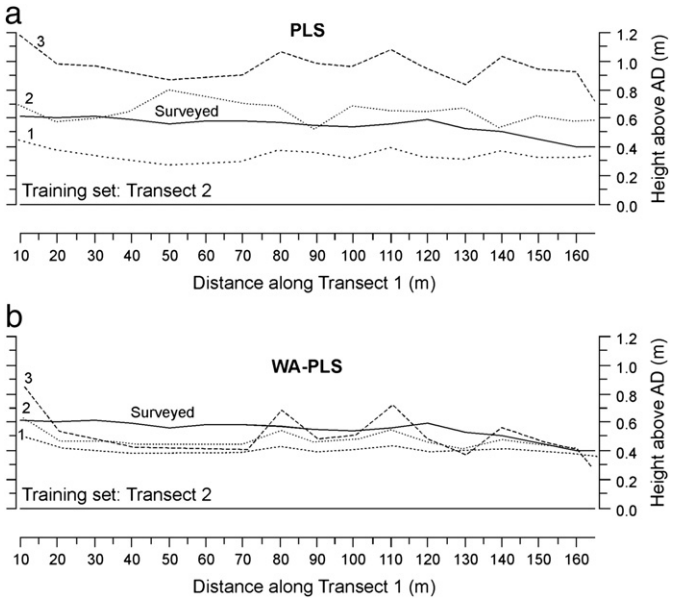

Fig. 4. a. Sample elevations of Transect 1 predicted by a training set containing samples from Transect 2 using PLS regression. b. Same, using WA-PLS regression. Predictions for the first three components are shown in each panel.

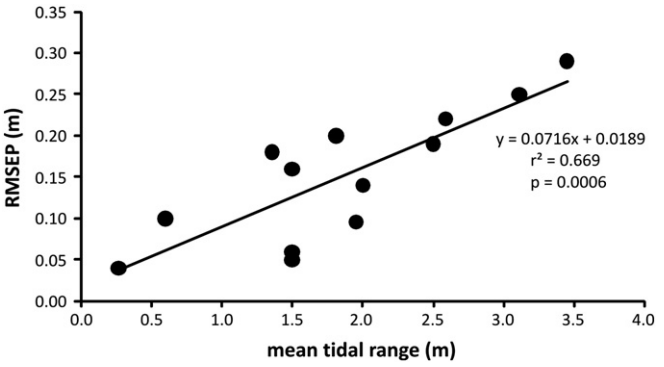

Fig. 5. Relationship between root mean squared error of prediction (RMSEP) and mean tidal range in 12 locations (Table 2). The most precise sea-level reconstructions can be made along coasts with small tidal ranges.

models overestimate most sample elevations along the lower part of the height gradient and underestimate elevations of many samples higher in the marshes. However, most residuals are less than 0.15 m. The three largest outliers are samples 39, 40 and 42, all in the lower part of the marsh (Fig. 3d). Sample 39 (90% *T. inflata* and *J. macrescens*) is predicted to be 0.18 m higher than observed. Sample 40 contains 20% *Quinqueloculina* spp. This species was removed from the training set and therefore the sample was predicted to be at an elevation that was 0.19 m higher than observed. Sample 42 contains the highest abundance (20%) of *H. wilberti* and the inferred elevation is too low by 0.19 m. We did not remove the outliers as we consider the samples to reflect the true variability of the training set.

Whereas the statistical parameters indicate which regression models perform best, they cannot account for the accuracy of palaeosea-level reconstructions based on transfer functions. In some studies, the reliability of sea-level reconstructions is checked by comparisons between reconstructions and nearby tide-gauge records (e.g., Gehrels et al., 2005, 2008; Charman et al., 2010). In this study we conducted an additional series of analyses on the modern training set data. Using the PLS and WA-PLS regression models we first calculated the statistical parameters for the individual transects (Table 1). They indicate that the training set from Watch House Bay (transect 1) is not suitable to be used by itself. Due to the low number of samples (17) the r^2_{jack} is very low and the WA-PLS model breaks down for component 3. For transect 2 the PLS models produce slightly better statistical parameters than the WA-PLS models, but when applied to reconstruct the elevations of transect 1 it becomes clear that the WA-PLS models produce more robust results (Fig. 4). Only the PLS reconstruction using component 2 seems realistic, but this is not reflected by the statistical parameters. The PLS model with the best statistical parameters (component 3) produces predictions that are outside the modern sampling range and exceed even the tidal range (Fig. 4a). This is a result of extrapolation inherent to linear regression models. Indeed, PLS models are rarely used in sea-level studies. Exceptions are the studies by Leorri et al. (2010) and Rossi et al. (2011) who applied PLS models to training sets from France and Portugal, respectively. Our results indicate that PLS models should be used with caution and their accuracy should be tested before they are applied to reconstruct past sea levels.

Table 2
Comparisons of modern foraminiferal data sets in selected salt marshes. A low RMSEP implies that sea-level changes can be precisely reconstructed from fossil foraminifera preserved in sediments. *N* — number of samples in training set. WA-Tol — Tolerance Down-Weighted Weighted Average regression. WA-PLS — Weighted-Average Partial-Least-Squares regression. PLS — Partial-Least-Squares regression.

Site	N	Model	RMSEP (m)	Mean tidal range	RMSEP/tidal range (%)	Reference
SW Pacific						
Tasmania	43	WA-PLS	0.10	0.60	16.7	This study
Catlins Coast, New Zealand	31	WA-Tol	0.05	1.50	3.1	Southall et al. (2006)
NE Pacific						
Oregon (average of 5 locations)	91	WA-PLS	0.20	1.81	11.0	Hawkes et al. (2010)
Eastern Atlantic						
Southwest England (average of 2 locations)	85	WA-PLS	0.29	3.45	8.3	Massey et al. (2006)
Western Denmark	16	WA-Tol	0.16	1.50	10.7	Gehrels and Newman (2004)
Brittany, France	43	PLS	0.22	2.59	4.6	Leorri et al. (2010)
Northern Spain (average of 4 locations)	30	WA-PLS	0.19	2.50	7.6	Leorri et al. (2008)
Northern Portugal	30	WA-PLS	0.10	1.95	3.7	Leorri et al. (2010)
Southern Portugal	22	PLS	0.14	2.00	7.0	Leorri et al. (2010)
Western Atlantic						
Nova Scotia, Canada	46	WA-Tol	0.06	1.50	3.7	Gehrels et al. (2005)
Maine, USA (average of 4 locations)	68	WA-PLS	0.25	3.11	7.9	Gehrels (2000)
Connecticut, USA (average of 4 locations)	91	WA-PLS	0.18	1.36	13.5	Edwards et al. (2004)
North Carolina, USA (average of 3 locations)	46	WA-PLS	0.04	0.27	14.8	Kemp et al. (2009)

4.4. Salt-marsh foraminifera as sea-level indicators

When foraminifera are used as sea-level indicators it is assumed, following the uniformitarian principle, that the vertical zonation of species has remained constant through time. The ecological parameter that controls the correlation of foraminiferal assemblages with elevation is duration of tidal flooding (Gehrels et al., 2001). It is difficult to test whether this parameter has remained constant, but the fossil assemblages we have encountered in cores (Callard, 2007) are identical to the assemblages found on the modern marsh surface. Moreoever, the inlet to the estuary is bedrock-framed, and it is unlikely that the tidal range has changed significantly during the last millennia, especially as sea level has remained close to its present level for at least 6000 years (Lambeck and Nakada, 1990).

In Table 2 we compare our results with other published foraminiferal studies from salt marshes. Although the precision of the foraminifera as sea-level indicators is good (±0.10 m), in other locations with small tidal ranges (e.g., New Zealand and North Carolina) foraminifera are found to be more precise sea-level indicators. Overall, the various studies that have been carried out around the globe show that the root mean square error of prediction (RMSEP), often taken as a measure of the indicative range, is strongly correlated with mean tidal range (MTR, Fig. 5). When the intercept is fixed at zero, this relationship is:

$$\mathrm{RMSEP} = 0.08 * \mathrm{MTR}$$

Clearly, the most precise sea-level predictions using foraminifera can be made along coasts with small tidal ranges.

5. Conclusions

Salt-marsh foraminifera in Tasmania are accurate and precise indicators of sea-level change. A training set of foraminifera consisting of forty-three samples collected from two transects in the Little Swanport Estuary (eastern Tasmania) shows that sea level can be predicted with a precision of ±0.10 m. The marshes contain *T. salsa* and *T. irregularis*, species which in other studies have been grouped as *T. salsa*. They are distinguished here because they inhabit different elevations and are therefore of value in sea-level studies. The accuracy of sea-level predictions was tested by using a training set from one transect to predict heights along the second transect. A Weighted-Average Partial Least Squares regression model was found to be robust and produced reliable results, while results of PLS models were demonstrably inaccurate. This study confirms the usefulness of salt-marsh foraminifera as sea-level indicators in the SW Pacific region. A comparison with studies from around the globe shows that sea-level reconstructions are most precise in microtidal settings.

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Appendix A

Transect 1: Watch House Bay.

Distance along transect (m)		0	10	20	30	40	50	60	70	80	89	100	110	120	130	140	150	160	165
Elevation (m above Australian datum)		0.634	0.604	0.614	0.614	0.574	0.544	0.554	0.564	0.594	0.584	0.594	0.584	0.564	0.534	0.514	0.454	0.404	0.404
Sample no.		n.a.	7	9	8	11	17	13	14	15	19	21	18	12	23	24	28	32	33
Counts																			
Trochammina inflata	Live	0	1	0	0	2	2	0	4	37	63	18	4	34	5	10	45	4	4
	Dead	2	57	96	272	141	288	250	228	105	108	202	83	155	165	117	192	105	159
	Total	2	58	96	272	143	290	250	232	142	171	220	87	189	170	127	237	109	163
Jadammina	Live	0	0	0	0	2	0	0	6	0	29	1	0	6	4	5	23	2	2
macrescens	Dead	0	79	113	249	85	29	50	81	62	204	92	73	104	54	231	154	104	72
	Total	0	79	113	249	87	29	50	87	62	233	93	73	110	58	236	177	106	74
Trochamminita	Live	0	1	0	0	0	0	0	0	6	1	2	4	0	0	6	5	0	13
irregularis	Dead	0	97	61	41	0	0	0	0	75	24	28	95	14	11	57	16	0	15
	Total	0	98	61	41	0	0	0	0	81	25	30	99	14	11	63	21	0	28
Trochamminta salsa	Live	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dead	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliammina fusca	Live	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dead	0	1	20	5	0	0	0	0	6	2	0	12	2	15	0	1	0	1
	Total	0	1	20	5	0	0	0	0	6	2	0	12	2	15	0	1	0	1
Elphidium sp.	Live	0	0	1	0	0	0	0	0	0	0	0	0	0	1	7	0	0	0
	Dead	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
	Total	0	0	1	0	0	0	0	0	0	0	0	0	0	4	7	0	0	0
Haplophragmoides	Live	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
wilberti	Dead	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	1	25
	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	1	25
Quinqueloculina sp.	Live	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Dead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	17
	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	18
Total counted		2	256	291	567	230	319	300	319	291	431	343	271	315	260	434	436	217	309
Total live		0	2	1	0	4	2	0	10	43	93	21	8	40	10	28	73	6	20
Total dead		2	254	290	567	226	317	300	309	248	338	322	263	275	250	406	363	211	289
Concentration (10 cc)		16	1862	15,520	3489	1227	1501	1600	4321	5912	11,259	4181	6194	1575	1387	1929	2325	789	1373

Transect 2: Lutrells Bay.

Distance along transect (m)		7.01	7.18	7.30	7.50	7.90	8.73	9.45	11.30	12.05	12.84	13.87	14.51	14.63	15.32	15.59	15.95	16.69	18.23	19.76	21.08	26.25	28.57	28.84	29.03	31.06	31.37
Elevation (m above Australian datum)		0.812	0.796	0.772	0.752	0.711	0.637	0.597	0.53	0.551	0.537	0.506	0.484	0.465	0.451	0.429	0.41	0.373	0.354	0.331	0.311	0.287	0.26	0.237	0.217	0.212	0.012
Sample no.		1	2	3	4	5	6	10	16	20	22	25	26	27	29	30	31	34	35	36	37	38	39	40	41	42	43
Counts																											
Trochammina inflata	Live	0	13	13	0	53	18	13	98	196	67	95	165	154	53	98	88	4	164	69	53	9	61	33	46	1	0
	Dead	15	48	56	15	343	123	370	261	224	138	182	531	161	191	126	137	110	203	161	85	103	180	115	129	155	166
	Total	15	61	69	15	396	141	383	359	320	205	277	696	315	244	224	225	114	367	230	128	112	241	148	175	156	166
Jadammina macrescens	Live	0	0	1	4	4	2	4	10	25	1	12	17	30	4	11	7	1	29	4	8	0	56	3	3	4	0
	Dead	11	18	16	21	43	58	74	67	138	70	81	126	67	64	37	92	19	77	102	103	12	55	52	41	113	30
	Total	11	18	17	25	48	60	78	77	163	71	93	143	97	68	48	99	20	106	106	111	12	111	55	44	117	30
Trochamminita irregularis	Live	0	0	27	9	3	6	0	1	4	0	1	9	10	5	3	2	0	3	0	1	0	1	3	0	0	0
	Dead	5	32	26	7	128	93	4	24	25	15	15	43	7	23	10	3	10	25	19	20	1	5	7	6	37	11
	Total	5	32	53	16	131	99	4	25	29	15	16	51	17	28	13	5	10	28	19	21	1	6	10	6	37	11
Trochamminita salsa	Live	8	28	0	12	10	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Dead	201	214	233	205	140	99	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	209	242	233	217	150	103	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliammina fusca	Live	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	0	1	0	0
	Dead	0	0	0	10	27	13	7	0	2	1	0	3	0	0	9	10	1	3	3	26	6	7	0	30	0	9
	Total	0	0	0	10	27	13	0	0	3	2	0	3	0	0	9	11	1	3	3	27	7	7	0	31	0	9
Haplophragmoides wilberti	Live	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	0	10	11	8	0	2	0
	Dead	0	0	0	1	1	21	0	0	2	1	0	6	0	0	0	0	0	0	4	0	2	4	8	4	77	48
	Total	0	0	0	1	1	21	0	0	3	1	0	6	0	0	0	0	0	0	7	0	12	15	16	4	79	48
Elphidium sp.	Live	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0
	Dead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0
Quinqueloculina sp	Live	0	0	0	0	0	0	0	16	1	3	3	40	0	25	0	0	0	13	43	36	0	3	7	56	0	0
	Dead	0	0	0	0	0	0	3	1	1	7	20	17	1	3	0	0	0	14	4	15	0	2	45	3	0	0
	Total	0	0	0	0	0	0	3	17	2	10	23	57	1	28	0	0	0	27	47	51	0	5	52	59	0	0
Total counted		240	353	372	284	753	437	475	479	620	304	409	957	430	368	294	340	145	541	412	349	143	385	281	319	389	264
Total live		8	41	41	25	70	30	17	125	228	72	111	231	194	87	112	98	5	219	119	100	19	132	54	106	7	0
Total dead		232	312	331	259	682	407	458	354	392	232	298	726	236	281	182	242	140	322	293	249	124	253	227	213	382	264
Concentration (10 cc)		3840	2840	2976	4544	12,048	13,984	7600	6387	9920	12,971	17,451	15,312	11,008	9421	4704	5440	464	8656	3767	5584	286	1540	3747	638	3112	4224

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